Paint vs. Performance – The Effects of Paint On Large Aperture Ka-Band Antennas

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Abstract—Non-uniform solar loading due to non-standard paint can cause a loss in earth terminal antenna gain and pointing inaccuracies due to dish defocusing, surface distortion and other changes in the structural geometry. Furthermore, paint and primer thickness less than a mil (one thousandth of an inch) is known to adversely affect the noise temperature, gain, and polarization isolation on high performance antennas [1].

In this paper, we describe the technical approach used to assess the effects of paint on an 18 m parabolic antenna. Using thermal and mechanical analysis based on the reflectivity and absorptivity properties of paint, we calculate the degradation on beam spreading and beam pointing losses in two pointing modes (Monopulse, and NORAD). Results of the analysis are used to show that end-to-end system performance (bearer traffic and command link availability margin), ground service availability, and Two Line Element set integrity can be maintained with an appropriate paint selection.

Keywords – satellite communications, earth terminal, Ka-band, paint, solar loading, RF effects, beam shape, noise temperature, pointing loss

I. INTRODUCTION

Many satellite communication systems for commercial television and radio applications, scientific research, and government and defense applications employ high-capacity high-frequency gateway links. As demand and spectrum scarcity drive satcom operating frequencies to 30 GHz and higher, larger diameter antenna earth terminal systems are required to produce higher gains for closure of these links to meet quality of service objectives.

Surface paints and primers are used as protective coatings to prevent oxidation and maximize heat dissipation. Due to the increasingly large dish diameters and increasingly small signal wavelengths, the effect of surface paints on the antenna assembly may become non-negligible. The microwave properties of the paint can cause phase distortions and mismatched reflections at the feed leading to increased VSWR. The thermal properties of the paint can cause increased uneven solar absorption leading to structural distortion and increased defocusing and pointing errors.

The standard surface paint color is white and very specific formulations of white paint are used. However, there are cases where non-standard paint color is chosen for the purpose of camouflage or aesthetics. For example, Ku Satcom dishes have been painted olive drab and desert tan colors for military applications [7].

The work described in this paper is motivated by a requirement to use non-standard paint color to blend in with the surrounding environment for aesthetic reasons. For our system, the use of aluminum-laminate reflector panels on a steel structure rather than composite material for the underlying earth terminal construction elevates the importance of analyzing the effect of the paint. However, the techniques described are also useful for evaluating different compositions of white paint for any type of material structure.

Earth terminal design and RF performance analysis and testing follow industry standards and is generally well understood. However, the effect of surface paints is not commonly analyzed in depth. In one of the few papers published on this subject [1], experimental and theoretical methods are used to determine the dielectric properties of several types of white paint for deep-space network earth terminals. The results, parameterized by paint thickness, are used as inputs to a model which produces the reflection coefficients and return loss. A second model then computes the increase in noise temperature and loss of antenna gain.

For our application, the impact of the microwave properties (dielectric constant) of the paint was judged to be much less significant than the impact of the thermal properties (absorptivity and emissivity) of the paint. In this paper, we investigate the thermal properties of two candidate non-standard paints to determine the temperature gradient across an 18-meter Cassegrain antenna for worst-case non-uniform solar loading. The thermal analysis results are used to determine the mechanical deflection and distortion of the parabolic reflector and support structure. The mechanical analysis results are then used to compute the RF link performance impact for both transmit and receive chains. The RF effects analyzed in this paper are categorized as Beam Spreading Loss and Beam Pointing Loss.

Beam Spreading Loss is due to reflector surface accuracy degradation resulting from uneven thermal deformation and antenna de-focusing due to changes in the relative positional relationship of the reflector, sub-reflector, and feed. The loss is measured as a three-sigma dB value, occurs in all tracking modes (acquisition, open-loop tracking, closed loop tracking) and is expected to be small.
**Beam Pointing Loss** is due to the disparity between the axis of the RF beam and the mechanical axis of the feed as measured by the azimuth/elevation encoders. The loss occurs only in acquisition and open-loop tracking modes. The loss is characterized as beam radial error (BRE) in degrees RMS. The one-sigma dB loss is computed from the BRE using the antenna gain versus the off-axis angle plots.

Once the RF link performance parameters are computed, then end-to-end system performance is evaluated. Link availability, service availability, acquisition time, pointing accuracy, and Two-Line Element set integrity are the metrics used.

This paper is organized as follows: the paint selection criteria is described in Section II, the techniques for thermal and mechanical analysis are given in Section III, the technical approach to compute RF link impact is provided in Section IV, pointing, acquisition and tracking is discussed in Section V, and the method of determining RF link impact on system performance is given in Section VI.

### II. PAINT SELECTION CRITERIA

Factors influencing the selection of paint include RF transparency at the frequencies of interest, compatibility with the antenna materials, environmental, safety, durability, transportation concerns, the thickness of the coating and any other RF effects that the paint materials may have. With all of these controlled, there is also the thermal effects of any given coating to consider. A thermal analysis model was used that employed vendor supplied paint properties of absorptivity and emissivity as the primary characteristics that effect the mechanical structure of an antenna. The first property of absorptivity is the amount of radiation absorbed by a surface compared to that absorbed by a black body [10]. The emissivity coefficient $\varepsilon$ - indicates the radiation of heat from a 'grey body' according the Stefan-Boltzmann Law, compared with the radiation of heat from a ideal 'black body' with the emissivity coefficient $\varepsilon = 1$ [11]. The Absorptivity and Emissivity values used in this analysis are given in Table I.

### III. THERMAL/MECHANICAL ANALYSIS

A thermal/mechanical analysis of the antenna structure was completed to assess the impact of a change in paint on the mechanical structure comprising the earth terminal. The model, using absorptivity and emissivity decomposed the earth terminal into four major assemblies:

- The reflector panels
- the sub-reflector structural support assembly
- the reflector structural assembly
- Lower base assembly

The lower base assembly consisted of the Elevation wheel, Elevation Bearing, Counter Weights, Yoke, Azimuth Bearing and Tower. Given an earth terminal at a fixed geographical location, elevation point angles, and diurnal solar cycle, the absorptivity and emissivity properties of the three paints can be used to obtain the temperature gradients for the antenna assemblies.

To find the antenna position for the highest temperature gradient, calculations were performed to determine the temperatures at different azimuth and elevation point angles that are consistent with the geometry of the ground location to satellite point angles and the diurnal cycle. After these calculations were performed, it was determined that thermal measurements taken on actual antennas would provide more detailed temperature data for use in the structural analysis. The result was a more accurate model of the thermal effects of the paint on antenna performance.

The thermal measurements were taken on two commercial 8 meter reflectors, one painted with white paint, the other with the option 2 paint. A thermal imaging camera was used throughout the day to capture the temperatures of the earth terminals side by side. The data from these thermal imaging tests was collected, compared to the calculations and used to provide more accurate temperatures for the structural analysis.

The structural analysis was performed using ANSYS [8] Finite Element Analysis (FEA) software. The software is used to find the deflections of each major assembly based on the predicted temperature data. Each model contains objects that represent the geometry of the structural components that comprise the four major assemblies. These objects are then characterized in the FEA using volume mesh hexahedron elements. The meshed elements are then manipulated with the temperature gradient results to compute the thermal deflections of the objects, and ultimately the distortions acting upon the four major structural components.

The volume mesh hexahedron element is set with properties that represent different beam type elements, shell elements, or element shapes. Each element then requires that material properties and attributes be assigned to them to represent the material in the assembly. To handle antenna tracking motion, structural criteria such as stiffness and weight of mechanical drives and bearings are also modeled by FEA. Using individual springs, beams and mass elements, the underlying physics and dynamics of the model are expressed by partial differential equations that are solved by numerical methods to minimize the error function and produce a stable antenna platform solution.

Changes to the antenna beam shape derived by distortions of the structure and the pointing, acquisition, gain and other RF impacts are discussed in section IV. The output of the refined FEA analysis predicts the effects of the thermal loading on the surface error budget summarized in Table II as contributions to beam radial errors in degrees RMS.

<table>
<thead>
<tr>
<th>TABLE I. PAINT THERMAL PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorptivity, $\alpha$</td>
</tr>
<tr>
<td>White</td>
</tr>
<tr>
<td>Emissivity, $\xi$</td>
</tr>
<tr>
<td>White</td>
</tr>
</tbody>
</table>

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TABLE II. SUMMARY THERMAL EFFECTS ON ANTENNA ERROR BUDGET

<table>
<thead>
<tr>
<th>Thermal Distortion Component in Degrees RMS</th>
<th>White Paint Error</th>
<th>Option 1 Paint Error</th>
<th>Option 2 Paint Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector Panels</td>
<td>0.0001</td>
<td>0.0033</td>
<td>0.0022</td>
</tr>
<tr>
<td>Reflector Substructure</td>
<td>0.0001</td>
<td>0.0005</td>
<td>0.0003</td>
</tr>
<tr>
<td>Subreflector mount motion</td>
<td>0.0021</td>
<td>0.0060</td>
<td>0.0040</td>
</tr>
<tr>
<td>Lower base (Elevation axis and lower)</td>
<td>0.0010</td>
<td>0.0022</td>
<td>0.0015</td>
</tr>
<tr>
<td>Error Budget Total</td>
<td>0.0033</td>
<td>0.012</td>
<td>0.0080</td>
</tr>
</tbody>
</table>

IV. RF LINK IMPACT

A. RF Gain Loss

The paint induced thermal structural deflections calculated by FEA are used as input to a proprietary numerical calculation that estimates the antenna gain performance (in dB).

This algorithm calculates the antenna far field radiation pattern based on the Uniform Theory of Diffraction method. Using this method, a Gain-Loss vs. Sub-reflector de-focus function can be constructed. Gain loss can then be found for a particular thermal distortion that is paint specific.

Due to the wide difference between Receive and Transmit bands at Ka band, the optimal sub-reflector position is adjusted for mid-transmit band, therefore the effect of thermally originated de-focusing is more pronounced on the Receive band (the antenna sub-reflector position before deformation is already slightly de-focused for the receive band).

RF gain loss on the transmit and receive signal paths is given in TABLE III.

TABLE III. EARTH TERMINAL RF IMPAIRMENT ANALYSIS

<table>
<thead>
<tr>
<th>Metric</th>
<th>White (dB)</th>
<th>Option 1 (dB)</th>
<th>Option 2 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX Spreading Loss (3σ, dB)</td>
<td>0</td>
<td>1.54</td>
<td>0.15</td>
</tr>
<tr>
<td>TX Spreading Loss (3σ, dB)</td>
<td>0</td>
<td>2.31</td>
<td>0.07</td>
</tr>
<tr>
<td>RX BRE Pointing Loss (1σ, dB)</td>
<td>1.09</td>
<td>Out of Range</td>
<td>2.90</td>
</tr>
<tr>
<td>TX BRE Pointing Loss (1σ, dB)</td>
<td>1.90</td>
<td>Out of Range</td>
<td>5.65</td>
</tr>
<tr>
<td>Acquisition Time (1σ sec)</td>
<td>68</td>
<td>Out of Range</td>
<td>89</td>
</tr>
</tbody>
</table>

As seen in TABLE III, the thermal/mechanical effects of the Option 1 paint, a darker paint with poor absorptivity and emissivity characteristics, had a greater negative effect on the beam shape, particularly the beam radial error. The option 2 paint that absorbs/retains less solar heat than the option 1 paint performed markedly better. Because the option 2 paint degradation due to solar loading is less, the distortion in the shape of the reflector and pedestal is less. Consequently the option 2 paint as modeled would perform better.

B. Group Delay and Gain Flatness

A cursory evaluation of group delay was undertaken with no indication of appreciable group delay effects. Group delay distortion resulting from thermally induced changes to antenna geometry is not significant because most of this distortion is a linear function of frequency and therefore non-dispersive. For reasons given respecting group delay, no appreciable effects are expected to the flatness across the frequency bands of interest.

C. Thermal Effects on Antenna Efficiency

No specific analysis trading antenna efficiency vs. RF link effects was made as part of this analysis. However, antenna efficiency is defined as the ratio of power into the antenna to the power radiated by the antenna. As such, antenna efficiency is not directly affected by the thermal effects reported herein because no loss of radiated energy is reported. The RF Gain model was run comparing a perfectly efficient antenna to a less efficient antenna with an equivalent additional surface error introduced into both. The resulting change in gain was the same for both the perfectly efficient antenna and the less efficient antenna.

V. POINTING, ACQUISITION, AND TRACKING

A. Pointing

Antenna pointing is estimated to be the greatest impact due to paint. The primary effect is gain loss due to Beam Radial Error (BRE). It occurs when there is a disparity between the axis of the RF beam and the mechanical axis of the feed as measured on the Azimuth and Elevation antenna position resolvers. When commanded to point at Azimuth X and Elevation Y, the antenna servo system uses readings from the resolvers to determine when an antenna is pointing at a precise AZ/EL bearing in space. There is a dependency on the alignment of the RF beam/antenna feed subsystem to the Servo subsystem. Following the calibration of the Servo system, it is assumed that the peak of the RF beam remains precisely aligned with the mechanical alignment of the antenna feed (feedhorn/ subreflector/ reflector combination).

When there is variation due to paint effects in the alignment of the mechanical feed to the RF beam, as measured in BRE, the result is to point the antenna away from its optimum alignment with respect to the peak of the RF beam. With an 18 meter aperture transmitting at 30 GHz, the RF half beamwidth (3 dB from peak power) is 0.02 degrees.

Antennas being pointed strictly using the mechanical feed/Servo mechanism, such as when acquiring, or if Monopulse mechanism is not available, have a gain loss due to BRE. This is true whether the Monopulse circuit has failed, or whether Monopulse is not operating because initial acquisition and transition to Monopulse mode has not occurred.
A further negative consequence of the misalignment of the RF beam to mechanical axis is in the development of satellite orbit prediction data (e.g. NORAD two-line element sets). Often, Two-line Element (TLE) sets rely on the integrity of the Azimuth and Elevation angle data collected when tracking a satellite to predict the satellite’s future orbit. An error in the alignment between the RF beam and the mechanical axis as reported by antenna AZ/EL resolvers induces a corresponding error into the prediction algorithm. The inaccurate pointing angles when used as the basis for calculating satellite orbit will propagate through the prediction generation resulting in reduced accuracy in the prediction tables and therefore increase the amount of time required to complete satellite acquisition.

B. Acquisition

Consider an ET acquisition time limit that allows for 2 minutes to point towards, acquire, and lock onto the satellite beacon. With a higher BRE, the antenna will have to scan a larger area of space to compensate for the higher BRE (unknown relationship or error between the mechanical point angle and the RF beam angle).

Much of the 2 minutes would be needed to accommodate a worst case Azimuth and/or Elevation movement to point the antenna roughly in the direction of the target. This leaves little time for the acquisition search algorithm to find the satellite beacon. The predicted worst case acquisition times can be found in TABLE III.

C. Closed Loop Tracking

In closed loop tracking, once the antenna acquires the satellite beacon, it executes a closed-loop tracking circuit. The closed-loop circuit feeds information about where the RF receive signal strength is stronger or weaker with respect to four quadrants of the aperture. The tracking circuit continually updates the antenna point angles to maximize signal power (keep the beacon on the peak of the RF beam). Once the target is acquired and enters a closed-loop tracking mode, analysis predicts that Monopulse tracking will maintain satellite track on the peak of the beam with only minor impact to receive gain.

In closed-loop tracking the error between mechanical ET feed axis and the RF beam is negated because the tracking circuit automatically keeps the antenna on the peak of the RF beam.

D. Open Loop Tracking

In open loop tracking the antenna calculates point angles from the antenna to the satellite location based on the antenna geographical location and the satellites predicted orbit. (e.g. NORAD two-line element set). In open-loop tracking the error between mechanical ET feed axis and the RF beam is significant. In the absence of a tracking circuit to keep the antenna on the peak of the RF beam, the antenna mechanically points to the predicted satellite location. Any disparity between the mechanical axis and the RF beam axis is not corrected, and RF performance is directly affected. The calculated RX and TX gain loss due to tracking error during open loop tracking is shown in TABLE III.

VI. SYSTEM PERFORMANCE ANALYSIS

Using the RF link impact results described in Section IV, the performance of the satellite communications system as a whole is assessed. First, the link availability for the gateway link (feeder link) using standard and non-standard paints is computed. Then the end-to-end link availability impact accounting for both the feeder link and the individual user terminal link is estimated. Finally, the feeder link ground service availability associated with the additional outage due to three-sigma beam pointing loss is calculated. The analysis culminates in the Supplier Technical Validation Risk and Opportunity Management Tool [5][6], where the results are used to produce likelihood and consequence assignments based on formal definitions. The structured process for identification, assessment, and handling of risks and opportunities leads to the final decision on paint selection.

A. Feeder Link Availability

For this work, link availability is defined as the fraction of any year that a communications link is able to support communications at the required rate and quality. The necessary equipment is assumed to be available. The link availability for satellite command links, telemetry and ranging links, and bearer traffic communications link are analyzed, but, only the traffic links are discussed in this paper to illustrate the technical approach.

The line items used in the link budget addressing the impact of paint are categorized as either gain losses or distortion. The two gain losses are beam spreading loss and cross-polarization losses. The two distortions considered are gain flatness and group delay deviation.

Cross-polarization losses are due to (1) the polarity misalignment (tilt angle or relative twist angle between the major axes of the incident wave and the receiving antenna) arising from pointing errors or atmospheric effects and (2) antenna axial ratio degradation due to changes in the feed or reflector. See the formula in Section 11.2 of [3] or [4]. For the link analysis we assume the worst-case polarity misalignment and assume the receive axial ratio degradation does not exceed 2.65 dB.

For standard paint, laboratory feed tests and reflector far-field tests at the unit level show the earth terminal complies with the axial ratio requirements (0.5 dB and 1.0 dB respectively) with large margin. Rain fade, the predominant atmospheric effect at the frequencies considered, causing both the worst-case polarity misalignment and worst case propagation amplitude link loss, is unlikely to occur at the time of maximum solar loading and worst-case axial ratio degradation.

If an on-orbit cross-polarization transponder is available, the deployed painted earth-terminal axial ratio can be measured in the field to verify the assumption of small changes in axial ratio. Clear-sky night measurements can be compared to clear-sky day time measurements performed at the predicted peak solar loading. Measurement accuracy of the on-orbit axial ratio test is limited by assumptions on the satellite transmit antenna axial ratio value, the polarity mismatch value, atmospheric effects on cross-polarization isolation and decoupling of the
uplink and downlink polarization isolation. For these reasons, the primary purpose of the test is to show that no large degradations in axial ratio are observed.

In the proposed test, a known Ka-band signal is transmitted from the earth terminal under test to the satellite which then retransmits the signal as either LHCP or RHCP to the earth terminal. Alternatively, a signal of a single polarity generated by the satellite is received by the earth terminal. The received signal is measured at the earth terminal RX LHCP and RX RHCP test ports. The power difference between the LHCP and RHCP test ports is the measured cross-polar interference. Using the measured cross-polar interference, the satellite transmit axial ratio, and the polarity mismatch set to unity (no mismatch) the earth terminal receive axial ratio is computed using the formula in [3].

In our application, the earth terminal transmit axial ratio has no significant impact on cross-polarization losses since the occupied RHCP and LHCP signal bands are non-overlapping in frequency.

The subject earth terminals feed high capacity satellites in the system which cover key theatres of operation. Fortunately, these links enjoy strong elevation angles to the satellites, smaller rain fades according to the ITU P.618 [2], and large link margins.

To analyze feeder link closure with worst case paint effects, we use

- Antenna gains 10 dB below nominal
- Cross-polarization loss with assumed worst case 2.65 dB axial ratio and worst case polarity mismatch
- Cross-polarization interference cancellation gain 4 dB below nominal
- Beam spreading loss according to TABLE III.
- Gain flatness and group delay distortion according to Section IV.B

With these impairments, the ground segment link is expected to meet C/N requirements for quality of service at the required link availability. The link shows sufficient margin to offset losses due to increased beam spreading loss and cross-polarization leakage associated with non-standard paint.

B. End-To-End Link Availability

At the system level link model, the earth terminal EIRP was set to a value lower than the nominal EIRP and the required RIP was set to a value higher than nominal to accommodate the sum of the beam spreading loss and the one-sigma pointing loss in TABLE III. The uplink and downlink feeder link availabilities are computed. Under the assumption that the Ka up and down links are composed of the same earth to satellite physical link, the composite Ka link availability (\( \ell_{Ka} \)) is chosen to be the lower of the up and downlinks.

The end to end link availability is computed as

\[
\ell_{N2N} = \ell_{User} \cdot \ell_{GroundNetwork} \cdot \ell_{Ka}
\]

The availability of the individual user link \( \ell_{User} \) is determined from dynamic multi-user link simulations and chosen to be the worst-case disadvantaged user. \( \ell_{GroundNetwork} \) is the availability for the ground network terrestrial link.

From this equation, we determine whether the end-to-end link availability meets user quality of service requirements such as BER, message loss probability, voice quality, latency, and the required link availability. Other system level requirements such as robustness, service duration, and coverage area were examined and judged to not be impacted by the earth terminal paint selection.

C. Service Availability

When the earth terminal equipment is not available or not functioning in the normal closed-loop monopulse tracking mode, outages not covered by link availability margin are booked in service availability. When the closed-loop tracking circuit fails, the earth terminal first falls back to open-loop tracking. If open-loop tracking is not operational, the system will switch operations over to the spare earth terminal.

The expected number of failures leading to either open-loop tracking or switchover and the predicted amount of time to acquire or resume closed loop tracking on either the originating earth terminal or the destination earth terminal is factored into the service availability calculation. Non-standard paint causes additional loss and outage time for acquisition captured in three-sigma Beam Pointing Loss (Section IV) and outage duration (Section V). The three-sigma losses are expected to occur less than once in the required ten year period of operations.

The service availability allocation shows sufficient margin to account for the additional 3-sigma outage time due to non-standard paint.

D. Risk Assessment

The analysis techniques (Sections III, IV, V, and VI) are applied to both candidate non-standard paints. The results are then used in a formal risk and opportunity management tool [5][6] to assess the threat. The option 1 paint performance consequence is assigned a rating of 3-4, which is defined as moderate to major requirement modification. The option 2 performance consequence is assigned a rating of 1-2, which is defined as no impact to minor requirement modification. This paint selection is recommended as the solution with minimal risk to system performance.

CONCLUSION

As demand for performance and profit drives satellite operating frequencies beyond 30 GHz, larger earth terminal antennas are required. Earth terminal performance becomes increasingly impacted by any degradation to surface accuracy or structural integrity leading to beam defocusing or pointing error. A technical approach to quantitatively characterize these errors as a function of surface paint non-uniform solar absorption is developed. Methods to assess system link availability performance using three-sigma beam spreading losses and one-sigma beam pointing losses due to paint effects
are described. Assessment of service availability using the three-sigma outage duration and expected number of occurrences is also provided. We conclude with a description of a structured process to assign risk and opportunity likelihood and consequence to each candidate paint selection. The result of our analysis is a paint selection which poses minimal risk to system performance while still meeting the original intended purpose.

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REFERENCES


